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# SEDS Tether M/OD Damage Analyses

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***November 1997***

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National Aeronautics and
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Marshall Space Flight Center

**_November 1997_**

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# SEDS TETHER M/OD DAMAGE ANALYSES

## 1. INTRODUCTION

The Small Expendable Deployer System (SEDS) was designed to deploy an endmass at the end of a 20-km-long tether which acts as an upper stage rocket. The SEDS components are the Deployer, consisting of the Deployer Canister, Core, and Baseplate; the Electronics Box; the Tether; the Brake/Cutter Assembly; and the Endmass.

The threats from the meteoroid and orbital debris (M/OD) particle impacts on any SEDS components are very important issues for the success of any SEDS missions. However, the possibility of severing the tether due to M/OD particle impacts is an even more serious concern for the success of any SEDS missions since the SEDS tether has a relatively large exposed area to the M/OD environments, although its diameter is quite small. The first three SEDS missions; i.e., SEDS–1, –2, and –3, used a tether which is 20 km long and 0.075 cm in diameter.

The threat from M/OD particle impacts became a very important safety issue for the SEDS–3 mission since the project office proposed to use the shuttle orbiter as the launch platform; the second stage of a Delta II expendable rocket was used for the first two SEDS missions. Figures 1 and 2 show the relative position and predeployment configuration of the SEDS–1 and –2 hardware on the second stage of the Delta II expendable rocket. Figures 3 and 4 show the relative position and predeployment configuration of the SEDS–3 hardware on the Hitchhiker crossbay carrier inside the orbiter cargo bay.

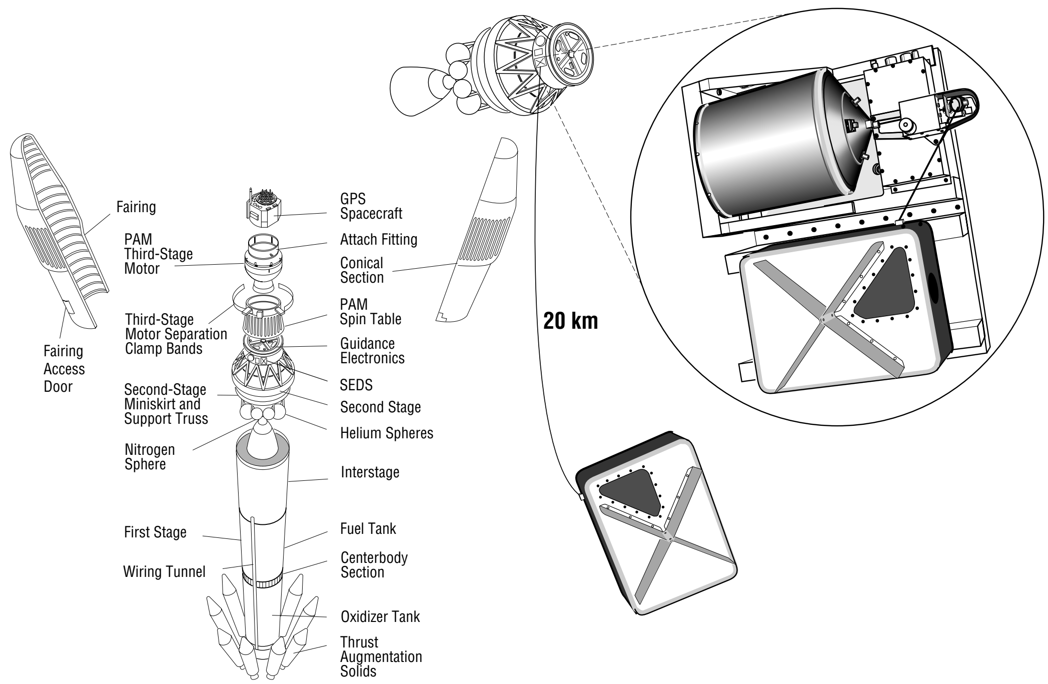


Figure 1. Location of SEDS hardware for SEDS–1 and –2 missions on the Delta II expendable rocket.

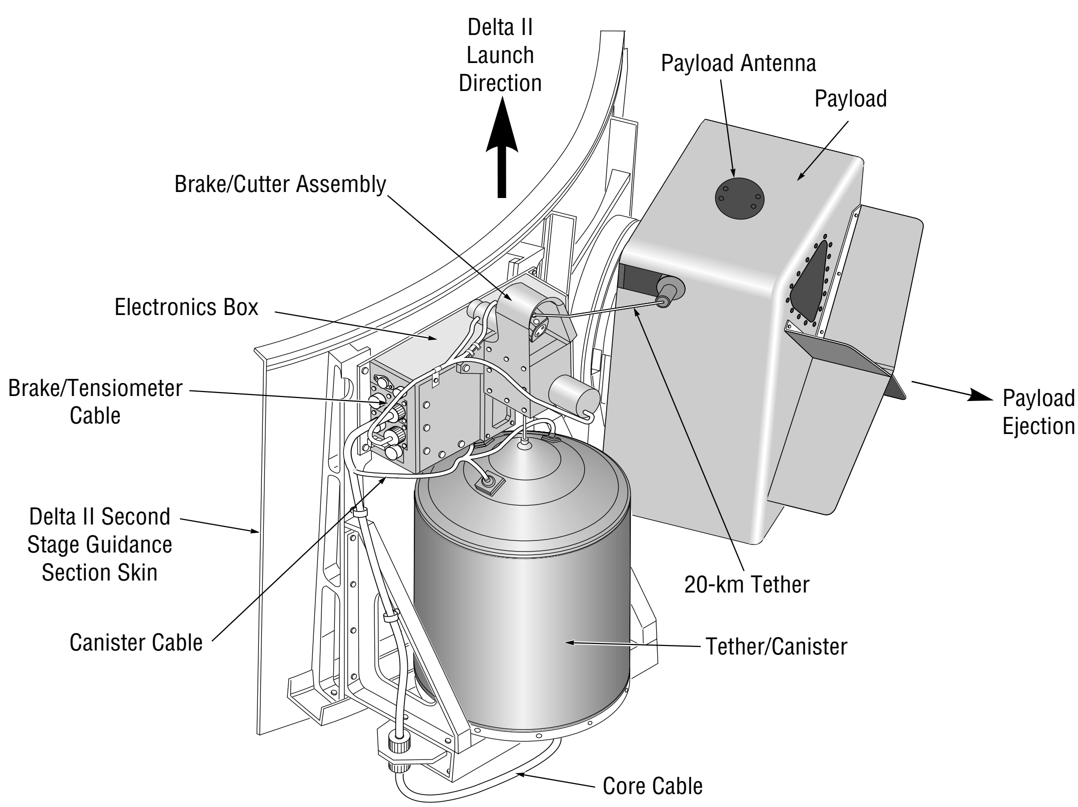


Figure 2. Predeployment configuration of SEDS hardware for SEDS–1 and –2 missions on the second stage of the Delta II expendable rocket.

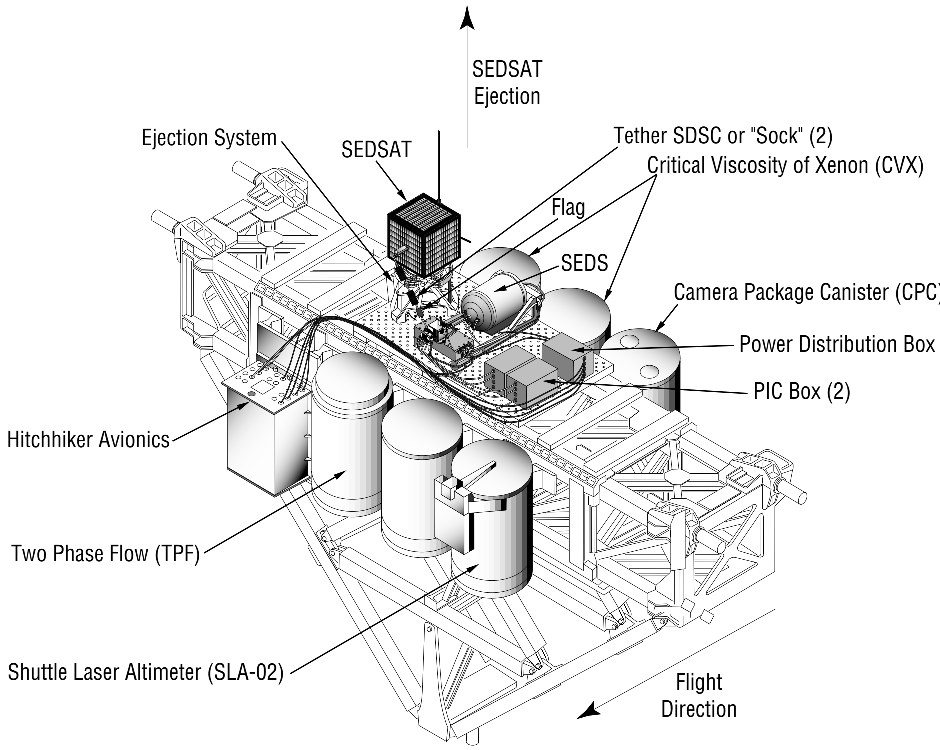


Figure 3. Location of SEDS hardware for SEDS–3 mission inside the shuttle orbiter cargo bay.

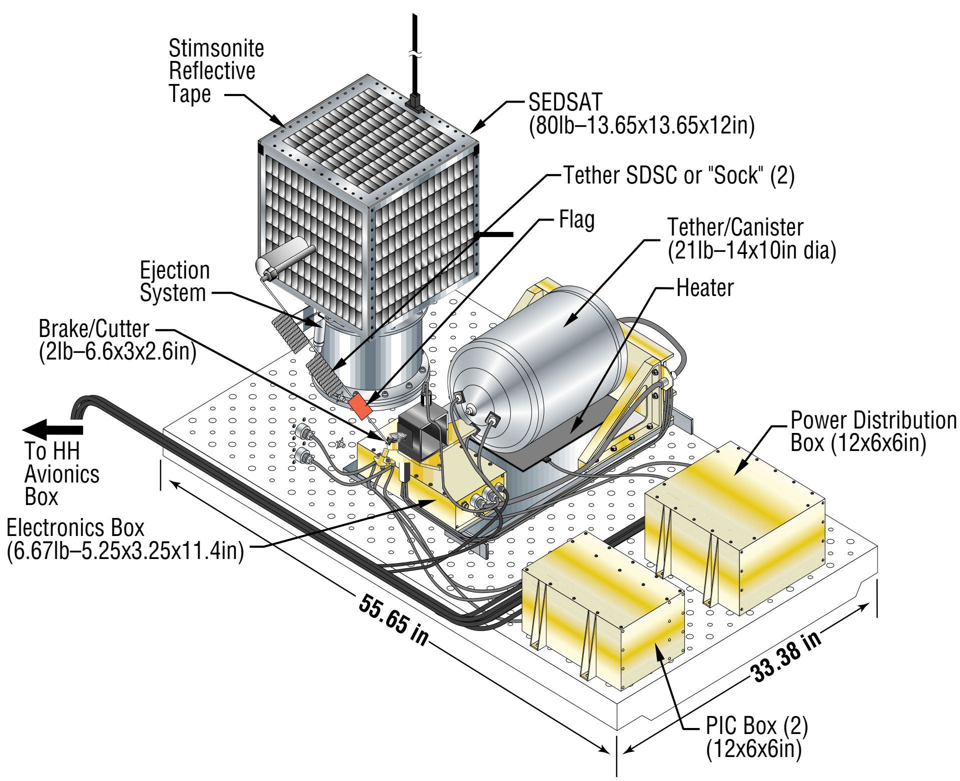


Figure 4. Predeployment configuration of SEDS hardware for SEDS–3 mission on the Hitchhiker crossbay carrier.

The tethers were deployed toward the Earth for both the SEDS–1 and –2 missions. The major objective of the SEDS–1 mission, which flew in March of 1993, was to verify the concept of using the tether as a deploying system. The major objective of the SEDS–2 mission, which flew in March of 1994, was to verify the control mechanism of the tether. However, the tether was planned to deploy away from the Earth for the SEDS–3 mission since it was the first SEDS mission to actually launch the payload. The SEDS–3 mission was proposed to fly in November of 1996 but was delayed to a later flight, June 1997. However, the mission was eventually canceled due to technical concerns. It was renamed the SEDS/SEDSAT mission when a small satellite called Students for the Exploration & Development of Space Satellite (SEDSAT) developed by the University of Alabama in Huntsville was chosen as the payload.

For the SEDS/SEDSAT mission, the possibility of an entanglement of a severed tether in the orbiter cargo bay or of damaging the orbiter due to a severed tether impacting the orbiter were areas of major consideration for the safety of both the orbiter and crew members. Therefore, determining the M/OD particle sizes required to sever the tether became more critical for the safety of the orbiter and crew members. Table 1 compares the three SEDS missions.

Table 1. Comparisons of three SEDS missions.

| | SEDS–1 | SEDS–2 | SEDS/SEDSAT |
|---|---|---|---|
| Launch Date | March 1993 | March 1994 | November 1996 |
| Mission Duration | 1 $^1/_2$ hr | 9 $^3/_4$ hr | 1 $^2/_3$ hr |
| Tether Length | 20 km | 20 km | 20 km |
| Tether Deployment | Downward | Downward | Upward |
| Launch Platform | Delta II Second Stage | Delta II Second Stage | Shuttle Orbiter |
| Mission Objective | Concept Verification | Tether Control Verification | Payload Boost |

The SEDS tethers are comprised of eight braided Spectra 1000 fibers, which are high-strength polyethylene fibers weighing 0.30 g/m (1.06 lb/mi). Although the tether has a high strength-to-weight ratio, the material has a very low melting point of 147 ºC (297 ºF). Since hypervelocity particle impacts create very high temperatures due to shock heating, the Spectra's resistance to the M/OD particle impacts was a major concern to determine the survivability of the tether in the M/OD environment. The critical M/OD particle sizes required to sever the tether as predicted by computer simulations and analyses were determined to be less than 0.1 cm in diameter. These particle sizes are expected to be more abundant in low-Earth orbit (LEO) than larger ones. The relative impact velocities to any orbiting spacecraft by the M/OD particles are an average of 20 km/sec (45,000 mph) and 10 km/sec (22,500 mph), respectively. Thus, the damage caused by these particles can be severe even though the expected M/OD particle sizes are very small. The M/OD damage analyses for the SEDS–1, –2, and SEDS/SEDSAT missions were performed by the authors and are discussed in this report. The M/OD damage analyses using empirically developed penetration equations and computer simulations using the CTH computer hydrocode predicted that the critical aluminum test particle sizes required to sever the tether are anywhere between 0.01 and 0.04 cm in diameter, depending on the assumptions made. Two analyses were completed for the SEDS–1 mission; only the second analysis attempts to account for the expected load on the tether. However, the empirically developed penetration equations used in these analyses are based on metals and are not accurate for nonmetals like Spectra, which is used for the tether. Also, the CTH computer hydrocode does not contain the equation of state for the tether material. Therefore, a series of hypervelocity impact (HVI) tests were performed to validate the analyses and to build up a database of the tether M/OD impact resistance capability for future missions.

Table 2 presents a summary of the three SEDS missions' parameters used for the M/OD damage analyses. The altitudes for the SEDS–1 and –2 missions are the average tether altitudes (the altitude at the midpoint of the deployed tether), and the altitude for the SEDS/SEDSAT mission is the planned shuttle orbiter altitude.

Table 2. SEDS mission parameters used for M/OD damage analyses.

| | SEDS–1 | SEDS–2 | SEDS/SEDSAT |
|---|---|---|---|
| Launch Date | March 1993 | March 1994 | November 1996 |
| Altitude | 735 km (397 nmi) | 342 km (185 nmi) | 297 km (160 nmi) |
| Inclination | 28.5° | 32° | 57° |
| Experiment Duration | 1.58 hr | 4.44 hr | 2.33 hr |
| Tether Dimensions | 20 km×0.075 cm | 20 km×0.075 cm | 20 km×0.075 cm |

## 2. METEOROIDS AND ORBITAL DEBRIS ENVIRONMENTS

During the early Apollo days, many studies were conducted to determine the effects of meteoroid particle impacts on spacecraft. As more and more spacecraft were launched into LEO, the generation of manmade orbital debris increased dramatically. Now, the threat of orbital debris is greater than that of meteoroids to most long-life orbiting spacecraft, while the meteoroid particle environment still remains the larger threat for other spacecraft components such as the impact-sensitive SEDS tether.

The meteoroid environment encompasses only particles of natural origin, and nearly all of the meteoroids originate from either comets or asteroids. There are two types of meteoroids: stream meteoroids, which retain their parent body orbit and create periods of high flux, and sporadic meteoroids, which randomly occur with no apparent pattern. The meteoroid environment is defined as the average total meteoroid environment which is comprised of the average sporadic meteoroids and a yearly average of the stream meteoroids. The recommended mass densities for meteoroids are 2 g/cm$^3$ for masses smaller than $10^{-6}$ g, 1 g/cm$^3$ for masses between $10^{-6}$ g and $10^{-2}$ g, and 0.5 g/cm$^3$ for masses above $10^{-2}$ g, although the mass density for meteoroids spans a wide range from 0.2 g/cm$^3$ or less for a portion of the population to values as large as 8 g/cm$^3$. This meteoroid distribution has an average relative velocity of 20 km/sec to an orbiting spacecraft, although the relative velocity to the orbiting spacecraft can go as high as 70 km/sec (156,600 mph) in LEO.

The meteoroid environment is again defined as the average total meteoroid environment which is comprised of the average sporadic meteoroids and the yearly average of the stream meteoroids. However, for the short-duration missions such as the SEDS missions, the stream meteoroids should be considered independently rather than as the yearly average. None of the analyses performed for the three SEDS missions considered the stream meteoroids or meteoroid showers independently, due to lack of availability of a model for stream meteoroids.

Within 2,000 km (1,080 nmi) altitude, there are about 200 kg (440 lb) of meteoroids with most of the mass concentrated in the 0.01-cm-diameter range. Within this same altitude range, there is an estimated 1M kg (2.2M lb) to 3M kg (6.6M lb) of manmade orbital debris as of mid-1995. Most of these orbital debris particles are in high inclination orbits where they sweep past each other at an average velocity of 10 km/sec.[1]

The orbital debris environment is comprised of about 1,500 spent rocket stages, inactive payloads, and a few active payloads. Recent observations indicate a total mass of about 1,000 kg (2,200 lb) for orbital debris with diameters of 1 cm or smaller and about 300 kg (660 lb) of orbital debris with diameters smaller than 0.1 cm. Unfortunately, the state of knowledge of orbital debris shape and density is very scant. Actual shapes are expected to be irregular, including flat plates, rods, hollow structures, and crumpled metal, although the sphere is assumed for the orbital debris environment model. However, the objects tend to be somewhat less irregular as size decreases.[2]

It is the nature of the M/OD environments that more of the smaller particles exist than the larger ones. Figure 5 shows this relationship for the representative M/OD environments for the SEDS–2 mission, which flew in March of 1994.

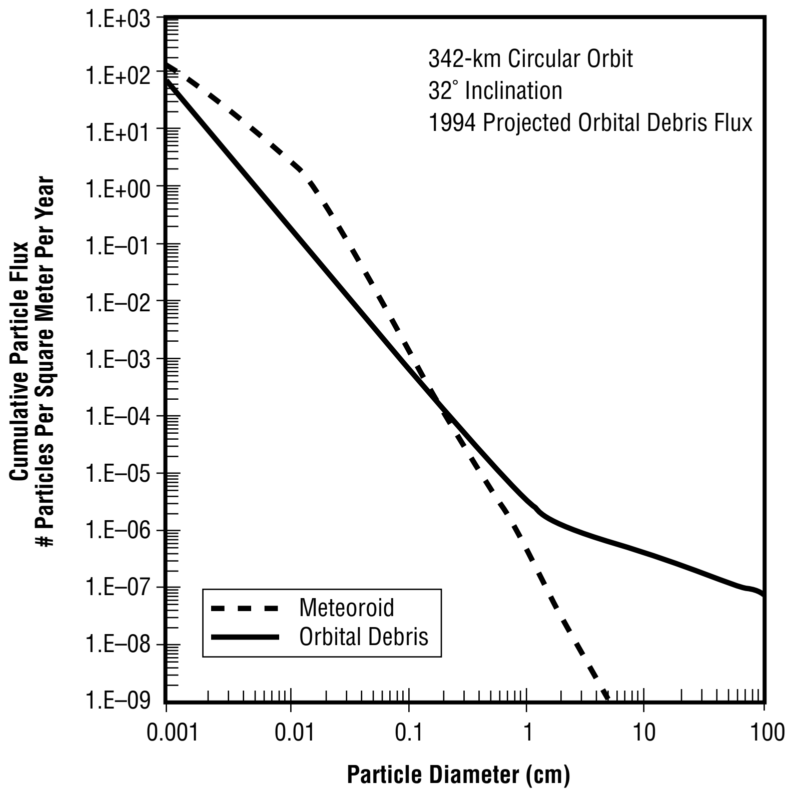


Figure 5. Cumulative particle flux as a function of particle diameter.

Determining a probability of no occurrence of random M/OD particle impact events is best done with the Poisson distribution.[3] Using the Poisson distribution, the equation applicable to determining the probability of no critical failure (PNCF) for a spacecraft or its components due to a meteoroid or orbital debris particle impact is

$$P_{\text{no critical failure}} = e^{-(\text{particle flux} \cdot \text{area} \cdot \text{time})} \, . \tag{1}$$

Here, the critical failures of spacecraft or its components are any failures which would prevent the accomplishment of a successful mission and/or would be threats to the safety of the spacecraft and/or its crew.

Then, the PNCF for a spacecraft or its components due to the combined M/OD environments is

$$P_{\substack{\text{no critical failure due}\\ \text{to M/OD particles}}} = P_{\substack{\text{no critical failure due}\\ \text{to meteoroid particles}}} \times P_{\substack{\text{no critical failure due}\\ \text{to orbital debris particles}}} \, . \tag{2}$$

Therefore, the probability of critical failure for a spacecraft or its components due to the combined M/OD environments is

$$P_{\substack{\text{critical failure due} \\ \text{to M/OD particles}}} = 1 - P_{\substack{\text{no critical failure due} \\ \text{to M/OD particles}}} \quad . \tag{3}$$

For the three SEDS missions, the critical failure of the tether was considered to be severing the tether instantly (the no-load case) or eventually (the load case) due to a meteoroid or orbital debris particle impact. Then, the equation applicable to determining the probability of no tether severing (PNTS) due to a M/OD particle impact has the same form as equation (1). Similarly, the PNTS due to the combined M/OD environments will be given by equation (2). And, the probability of tether severing due to the combined M/OD environments will be given by equation (3).

The orbital debris particle flux is a function of the actual month and year of the mission, the solar flux of the previous year, the mission altitude and inclination, and the critical particle size. The meteoroid particle flux is a function of only particle size and altitude, the model having been integrated over time to include all sporadic and stream meteoroids which occur throughout the year. As equation (1) shows, the probability of no tether severing due to a meteoroid or orbital debris particle impact is dependent on the exposed area, the exposure time, and the particle size required to sever the tether at the average expected impact velocity. The data specific to each of the SEDS missions are given in tables throughout this paper. Some of the differences in the PNTS calculations from one mission to the next are due to improvements and refinements in the analysis assumptions and techniques.

## 3. SUMMARY OF HYPERVELOCITY IMPACT TESTS

The threat of M/OD particle impacts on any SEDS hardware or tether are very important issues for the success of SEDS missions. Grazing or partially penetrating impacts can cause degradation of the tether's load capability and eventual severing of the tether. A more serious concern is the possibility of severing the tether instantly. The SEDS tether has a relatively large exposed area to the M/OD environments, because of the extremely long length of the tether. However, the expected M/OD particle sizes required to sever the tether are very small since the cross-sectional diameter of the tether is very small.

A series of HVI tests are usually performed to help determine the critical particle sizes required to cause the critical failure of the spacecraft or its components. However, there is a major limitation in the test capability which is the maximum launch speed of the test facilities. Particles can only be launched at less than 8 km/sec at an affordable cost, and with a certain degree of confidence in existing HVI test facilities; the average expected impact velocities of M/OD particles are 20 km/sec and 10 km/sec, respectively. In addition to this limitation, testing the SEDS tether presented a unique problem in launching a dust-size particle into the very thin tether target. Two HVI test facilities, the NASA/JSC and AEDC, were used to test the SEDS tether.

After the SEDS tether was severed during the SEDS–2 mission, a series of HVI tests were performed at the Hypervelocity Impact Test Facility (HIT–F) at JSC using a two-stage light-gas gun to simulate hypervelocity M/OD particle impacts. The results of the tests were intended to identify the particle size required to instantly and completely sever the tether. The tests were performed with no-load on the tether other than that required to keep the tethers straight on the test fixture. The technique used by JSC launches a single particle at multiple tether targets to increase chances of hitting at least one target. The results from these laboratory tests showed that the aluminum test particles impacting tether samples at approximately 6.5 km/sec would sever the tether when the aluminum test particles were between 0.035 and 0.040 cm in diameter. Because these test particles are very small, and the orbital environment contains more small meteoroids than orbital debris particles, it was concluded that the most probable critical particle required to sever the tether was a smaller meteoroid at a higher impact velocity.

Another series of HVI tests were later performed at the Hypervelocity Impact Range of AEDC in Tullahoma, Tennessee, using another technique to obtain more definitive test results and to support the SEDS/SEDSAT mission. The tests were performed using a two-stage light-gas gun with a 1-lb weight attached to each tether, simulating an expected normal load during the deployment of the endmass. The technique used by AEDC was expected to increase the chances of a successful test by impacting multiple tethers with multiple test particles, in terms of tens or hundreds of test particles, instead of shooting a single test particle at multiple tethers. Simulation results from computer hydrocodes indicated that the critical aluminum test particle sizes required to sever the unloaded tether would be between 0.015 and 0.020 cm, much smaller than the aluminum particle sizes available for the HVI test. Thus, smaller glass test particle sizes were requested for the remaining tests at AEDC to verify the computer simulation results and to better determine the critical glass test particle sizes. The test results indicated that the glass test particles impacting tether samples at approximately 7 km/sec would sever the 1-lb loaded tether when the glass test particle sizes were between 0.030 and 0.035 cm. These glass test particle sizes are smaller than the aluminum ones from the previous tests but are larger than the aluminum ones predicted by the computer simulations. Computer simulations with glass particles were not performed since the density of the glass particles used in the tests were 2 g/cm$^3$, nearly that of aluminum which is 2.8 g/cm$^3$. Usually the material density is the most important property for projectiles in HVI. As the SEDS missions were evaluated, more and different test techniques and analyses were used to improve upon previous analyses. The results described above were considered in the selection of the critical particle sizes for each mission. These particle sizes can be found in tables 3 through 5 and 7 and 8 in section 5.

Although two different techniques were used to test the SEDS tether, the ability to hit the very small diameter tether with a dust-size test particle proved troublesome; however, there were several successful tests performed. The test results indicated that further development of test techniques is desirable and recommended for future tether tests.

# 4. HYDROCODE ANALYSES

The computer hydrodynamic code or hydrocode named CTH, developed by Sandia National Laboratories, was used to simulate the damage on the tether due to the orbital debris or aluminum test particle impacting on the tether. The CTH hydrocode is a fully three-dimensional Eulerian hydrocode capable of modeling a wide range of impact and shock physics problems.[4] It has the capability to model one-dimensional problems in rectangular, cylindrical, and spherical coordinates; two-dimensional problems in rectangular and cylindrical coordinates; and three-dimensional problems in rectangular coordinates.

The first simulations made with CTH were to analyze the damage on the SEDS tether caused by an orbital debris particle impact in order to support the M/OD damage analysis performed for the SEDS–1 mission. The impact of an orbital debris particle on both a single-strand and an eight-strand cross-section, 0.075 cm in diameter, were analyzed in these first simulations. Both simulation geometries involved a 0.005-cm titanium sphere, impacting the tether at a velocity of 10 km/sec, the average impact velocity to a spacecraft by orbital debris particles in LEO.

The CTH hydrocode offers equations of state for numerous materials. However, the CTH hydrocode did not provide the equation of state for Spectra 1000, a high-strength polyethylene. Thus, the equation of state for polystyrene with the density scaled to that of the Spectra 1000 was used for the simulations, since polystyrene was the closest material found in the CTH hydrocode material equation of state database.[5,6]

The first simulation was constructed in two dimensions with the particle impacting onto a single 0.075-cm strand of the tether. The simulation was stopped after 0.4 $\mu$sec since crater advancement had slowed significantly. This simulation resulted in a crater depth of approximately 40 to 50 percent of the diameter of the strand. The second simulation was also constructed in two dimensions with the particle impacting onto an eight-strand bundle tether that was 0.075 cm in overall diameter. This simulation was stopped after 0.18 $\mu$sec with a crater depth of approximately 40 to 50 percent of the diameter of the overall bundle. Due to the low melting point of the material used in this simulation, the entire eight-strand bundle appears to have melted into one large bundle. Due to the nature of modeling three-dimensional geometries in two dimensions, both cases are actually a plane strain simulation of a small diameter cylinder impacting a much larger diameter cylinder, as in the first case; or a bundle of cylinders, as in the second case. The results of this plane strain model is that the initial compressive shock continues on in the material infinitely with no rarefaction wave releasing the compressive state in the material. This results in higher temperatures being generated in the shocked material. Figures 6 and 7 show the first and last time step of the integration for each simulation. These plots show the material density with the darker gray as the most dense material.

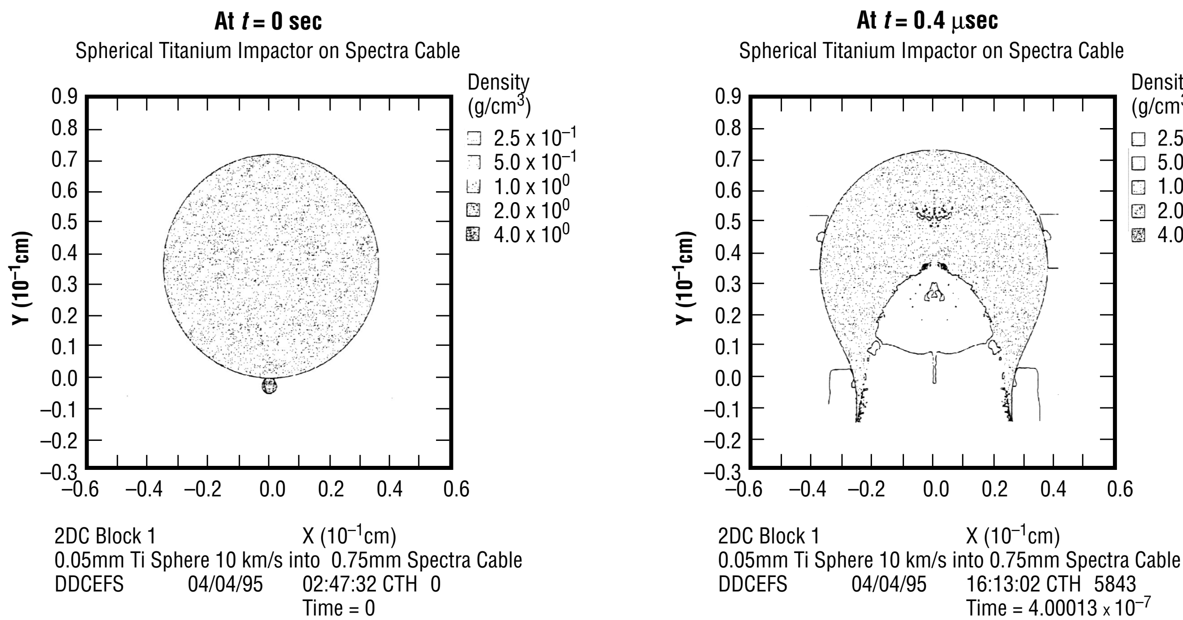


Figure 6. CTH hydrocode two-dimensional simulation results using a single-stranded tether and a titanium projectile.

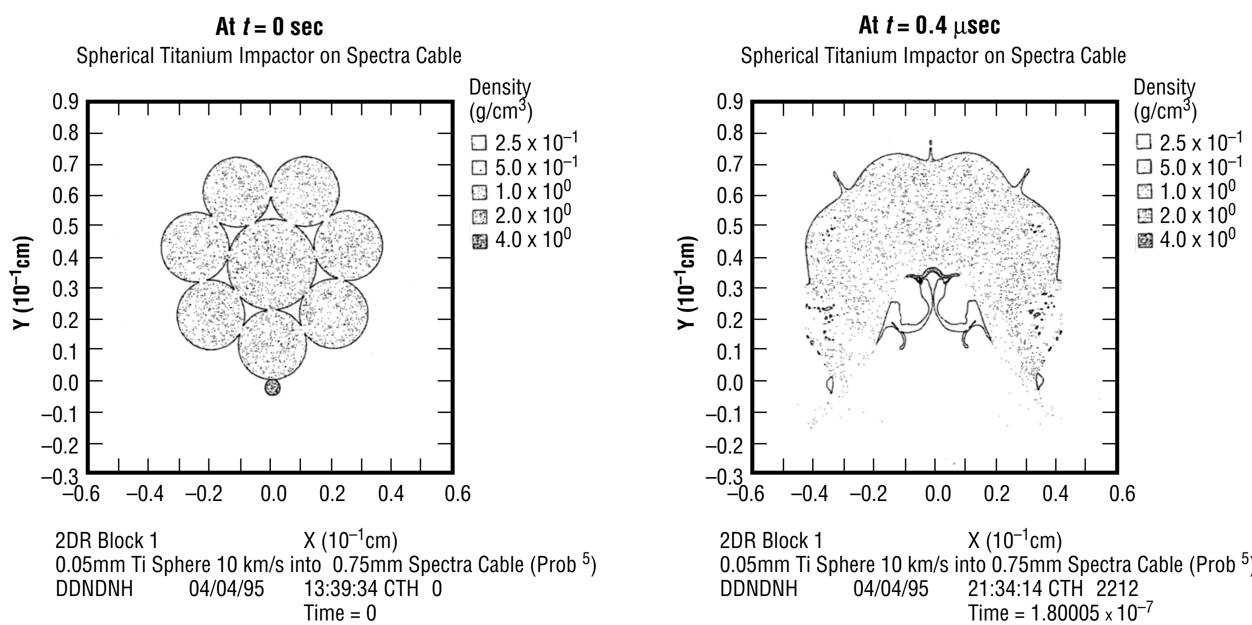


Figure 7. CTH hydrocode two-dimensional simulation results using an eight-stranded tether and a titanium projectile.

Uncertainty in the computer simulations arises from not having the appropriate equation of state for the tether material, Spectra 1000, and using that for polystyrene instead. Another point of uncertainty in this analysis arises from performing the computer simulations in two dimensions, which resulted in an infinitely long titanium cylinder impacting onto the infinite cylindrical tether. This situation adds conservatism to the result since the shock wave occurring in the *z*-direction never reflects, thus the compressive state in the projectile is not released. If the compressed matter in the projectile were allowed to release, as in the case of a spherical projectile, the projectile would begin to break up earlier and, therefore, result in less damage to the target. Even though both computer simulations yielded similar amounts of damage to their respective tether targets, they both appear to overpredict the amount of damage by a factor of two when compared to empirical penetration equations, although the penetration equations were developed for metallic projectiles and targets.

Later, a second attempt was made with the CTH hydrocode to help predict the critical aluminum test particle sizes required to sever the tether in order to support the M/OD damage analysis performed for the SEDS/SEDSAT mission instead of predicting the critical orbital debris particle sizes, as previous computer simulations used. The main difference in these simulation cases from the previous cases is the use of an aluminum particle impacting the tether at 7 km/sec versus a titanium particle impacting at 10 km/sec. Two cases, a single-strand the diameter of the tether and an eight-strand cross section, were again used to simulate the impact of the aluminum test particles, and the equation of state of polystyrene with the density scaled to that of Spectra 1000 was once again used as the equation of state for the target. A series of computer simulations were constructed in two and three dimensions with the particle impacting onto a single 0.075-cm strand of tether and an eight-strand bundle tether that was 0.075 cm in overall diameter. The first particle size simulated was 0.035 cm in diameter; then the particle size was reduced in 0.005-cm increments to find the particle size that would not sever the tether. Due to the low melting point of the material used in these simulations, the entire eight-strand bundle appeared to have melted into one large bundle as discussed previously. Figures 8 and 9 show the top and side views of the first and last time step of the integration for the three-dimensional simulation using a 0.015-cm aluminum test particle impacting at 7 km/sec onto a single-stranded tether. Figures 10 and 11 show the top and side views of the first and last time step of the integration for the three-dimensional simulation using the same size test particle impacting at the same velocity onto an eight-stranded tether. As in previous simulations, uncertainty in the simulations arises from not having the appropriate equation of state for the tether material, Spectra 1000, and using that of polystyrene instead.

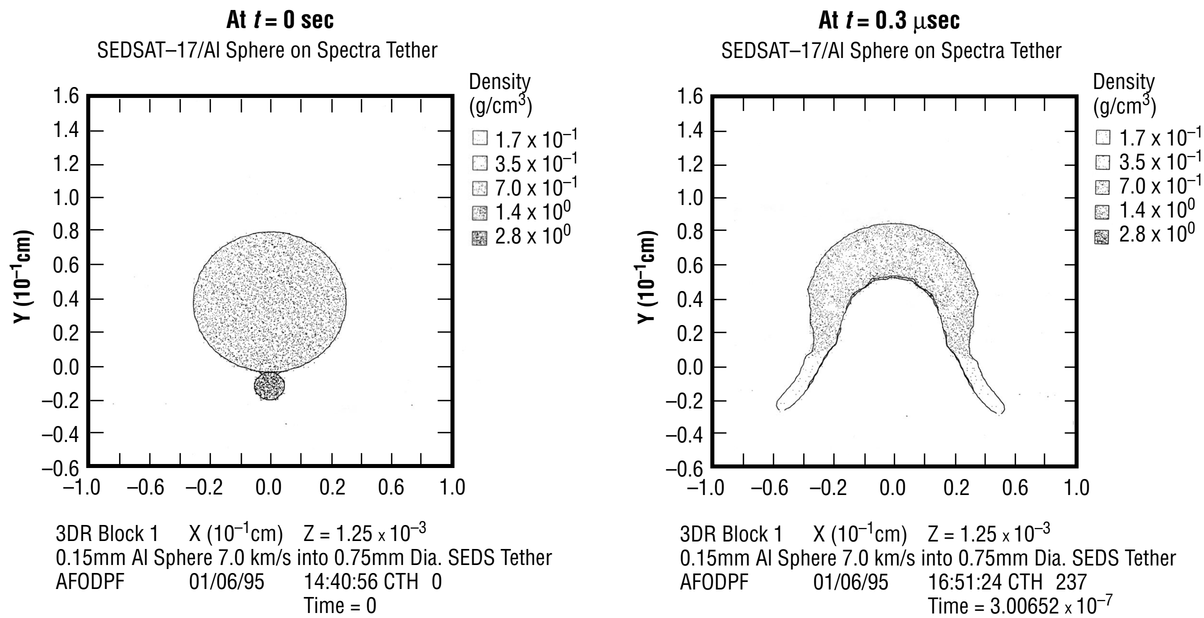


Figure 8. CTH hydrocode three-dimensional simulation results using a single-stranded tether and an aluminum projectile (top view).

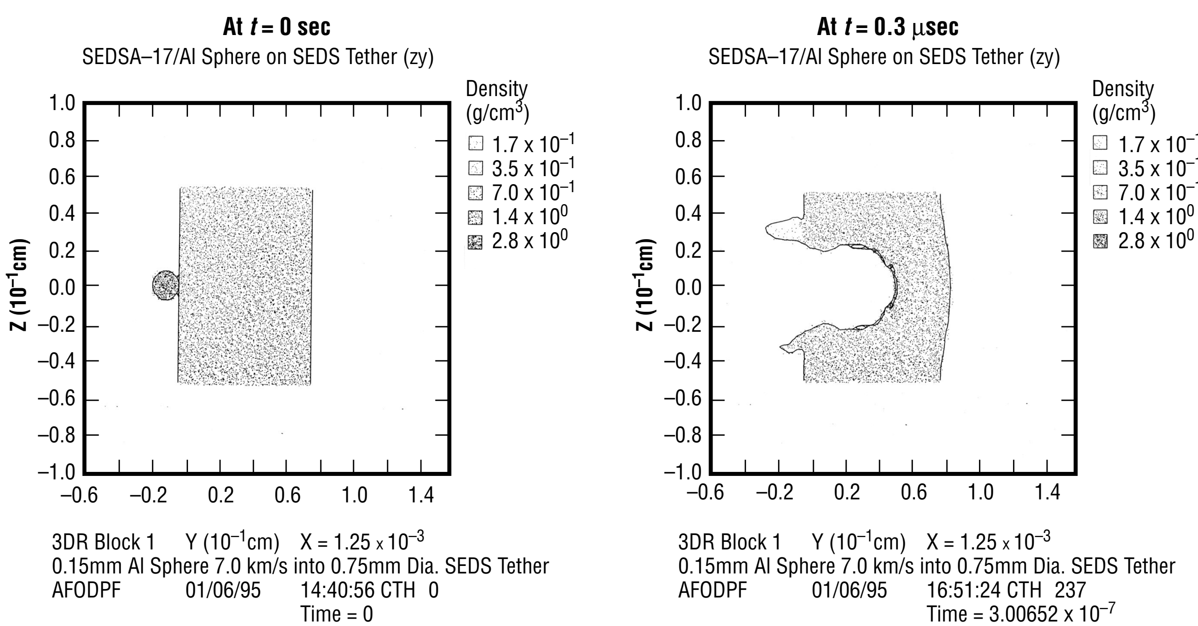


Figure 9. CTH hydrocode three-dimensional simulation results using a single-stranded tether and an aluminum projectile (side view).

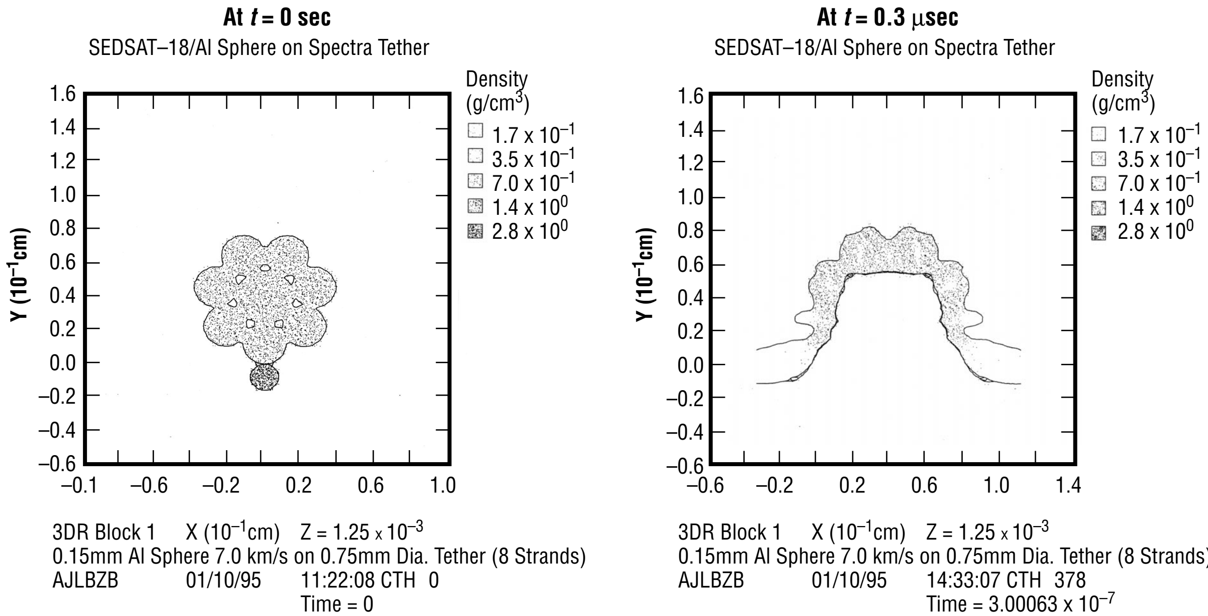


Figure 10. CTH hydrocode three-dimensional simulation results using an eight-stranded tether and an aluminum projectile (top view).

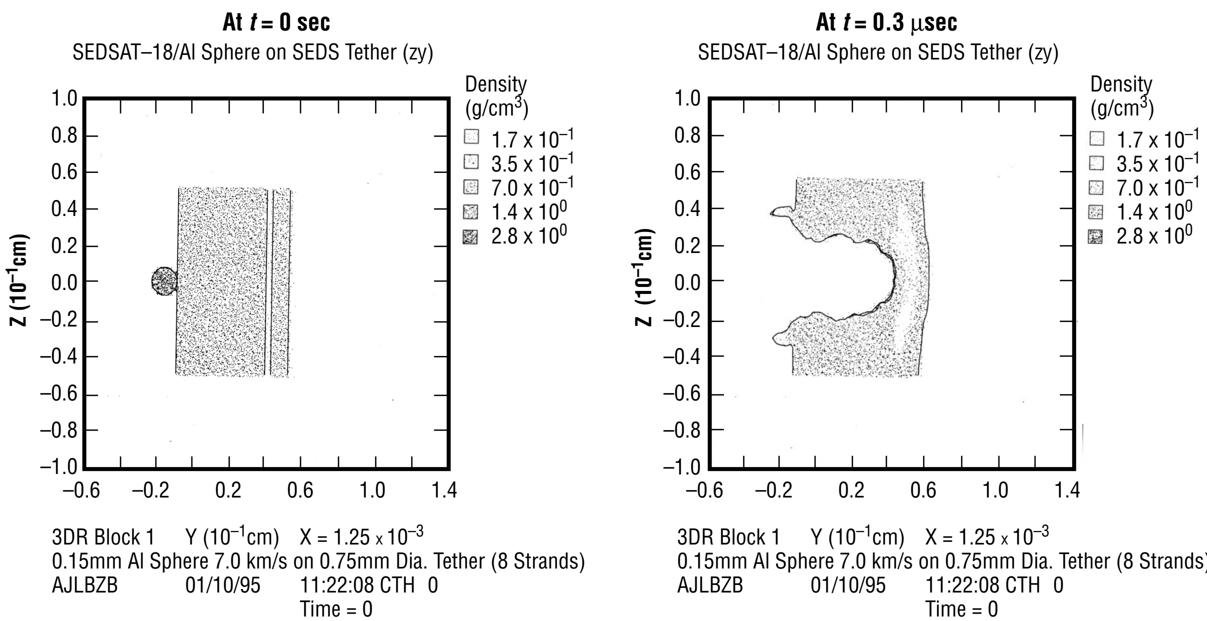


Figure 11. CTH hydrocode three-dimensional simulation results using an eight-stranded tether and an aluminum projectile (side view).

## 5. METEOROID AND ORBITAL DEBRIS DAMAGE ANALYSES

The following sections discuss the M/OD damage analyses performed for the SEDS–1, –2, and –3 missions in detail. As discussed in previous sections, the HVI tests and CTH hydrocode simulation results provided the much needed information to help determine the critical particle sizes required to sever the tether.

### 5.1 First SEDS (SEDS–1) Mission

Due to lack of empirical penetration equations involving Spectra 1000 tether material and the impact geometry, a single, thick-plate penetration equation was employed to estimate the projectile diameter that would cause the tether to fail.[3] The material constant used in this equation was estimated for Spectra by using the ratio of the material density to known densities for known material constants. Based on information concerning the strength of the tether and the flight loads on it, failure of the tether was estimated to have occurred if the impact crater exceeded half of the overall diameter of the tether. The failure of the payload cover was estimated using the Fish-Summers single, thin-plate penetration equation.[7] Using these assumptions and the aforementioned penetration equations, the probability of no failure of the tether and the payload cover was estimated at 99.45 percent, total for the M/OD environments. Individually, the probability of no failure of the tether was 99.45 percent, and the probability of no failure of the payload cover was better than 99.99 percent. For this analysis, the M/OD models were used as defined in NASA SSP–30425, Rev. A.[8] The resulting critical projectile sizes and exposed areas to the M/OD environments used are given in table 3.

Table 3. M/OD impact damage analysis results for SEDS–1 tether (unloaded) and payload cover.

| | Tether | Payload Cover |
|---|---|---|
| Exposed Area to Orbital Debris Environment | 32.10 $m^2$ | 0.54 $m^2$ |
| Exposed Area to Meteoroid Environment | 32.10 $m^2$ | 0.54 $m^2$ |
| Orbital Debris Particle Size to Cause Failure | 0.0156 cm | 0.0337 cm |
| Meteoroid Particle Size to Cause Failure | 0.0162 cm | 0.0351 cm |
| Probability of No Failure by Each Component | 99.45% | 99.99% |

A second assessment of the SEDS–1 tether was later completed, given that some controversy existed over the orbital debris environment definition and the capability of Spectra 1000 to resist the M/OD particle impacts. In this analysis, material test data were included which showed that the tether lost 7-lb of load-carrying capability with a tether mass loss of 0.85 percent. Based on this ratio, the impacting particle size was determined which would cause the tether to break under a 5-lb design break load; a factor of safety of two was used on this load. For this assessment, a tether length of 22 km rather than 20 km was used for a more conservative analysis. Many unknowns remained in the analysis, resulting in a probability of no failure between 55 and 84 percent, depending on assumptions made about the tether reaction to hypervelocity particle impacts. The M/OD environment models used were those defined in NASA SSP–30425, Rev. A, Change A1.[9] These models are the same as the most current published M/OD models, found in NASA

TM–4527 entitled, “Natural Orbital Environment Guidelines for Use in Aerospace Vehicle Development,” June 1994.[2] Table 4 summarizes the critical particle sizes, the tether exposed area to the M/OD environments, and the resulting probability of no tether severing for the last SEDS–1 tether failure analysis.

Table 4. M/OD impact damage analysis results for SEDS–1 tether (loaded).

| | |
|---|---|
| Exposed Area to Orbital Debris Environment | 51.84 $m^2$ |
| Exposed Area to Meteoroid Environment | 51.84 $m^2$ |
| Orbital Debris Particle Size to Sever the Tether | 0.0036–0.0062 cm |
| Meteoroid Particle Size to Sever the Tether | 0.0031–0.0054 cm |
| Probability of No Tether Failure | 55%–84% |

In addition to this analysis, an attempt was made with the CTH hydrocode to simulate the damage on the SEDS tether by the orbital debris particle impact, discussed in detail in section 4. These simulations resulted in a crater depth of approximately 40 to 50 percent of the tether diameter by the 0.005-cm titanium projectile traveling 10 km/sec simulating the orbital debris particle in LEO.

### 5.2 Second SEDS (SEDS–2) Mission

The damage analysis of the SEDS–2 tether was similar to the analysis of the SEDS–1 tether for the loaded case. The material and tether diameter remained unchanged, so the determination of the critical M/OD particle sizes required to sever the tether also remained the same. However, the mission duration is longer, resulting in a lower probability of no tether severing, ranging from 48 to 79 percent, depending on assumptions made about the Spectra 1000 tether’s reaction to hypervelocity particle impacts. The parameters used in this analysis are given in table 5.

Table 5. M/OD impact damage analysis results for SEDS–2 tether (loaded).

| | |
|---|---|
| Exposed Area to Orbital Debris Environment | 82.65 $m^2$ |
| Exposed Area to Meteoroid Environment | 47.12 $m^2$ |
| Orbital Debris Particle Size to Sever the Tether | 0.0036–0.0062 cm |
| Meteoroid Particle Size to Sever the Tether | 0.0031–0.0054 cm |
| Probability of No Tether Severing | 48%–79% |

The following events occurred during the SEDS–2 mission:

| | |
|---|---|
| 3/10/94, 2:40 G.m.t. | Delta II Launch |
| 3/10/94, 3:45 G.m.t. | Tether Deployment Began |
| 3/10/94, 5:31 G.m.t. | Tether Deployment Concluded |
| 3/15/94, Between 0:15 & 1:46 G.m.t. | **Tether Severed** |

Following the severing of the SEDS–2 tether in March 1994, an update to earlier assessments attempted to determine the severing M/OD particle sizes for the tether and the most likely M/OD particles to occur with the 4.82 days of tether exposure. A series of HVI tests began at JSC’s HIT–F to simulate hypervelocity M/OD particle impacts. The results of the tests were intended to identify the particle size required to sever the tether instantly and completely. From these test results, aluminum test particles impacting tether samples at approximately 6.5 km/sec would sever the tether when the test particles were between 0.035 and 0.040 cm in diameter. Because these test particles are very small, and the orbital environment contains more small meteoroids than orbital debris particles, indications are that the most probable critical particle was a smaller meteoroid at a higher impact velocity.

To check previous assessments and to get a better idea of the severing particle size, the particle which has a frequency of one in 4.82 days was backed out of the defined M/OD models. The exposed areas used in the analysis included the effects of the directionality of orbital debris, which has the effect of a larger exposed tether area to the orbital debris environment, and resulting in a higher overall probability of tether severing. From these models, the particle most likely to occur once in 4.82 days is expected to be a meteoroid with a diameter $\geq$0.014 cm. However, because the M/OD particles impact randomly with size, velocity, and angle, it is impossible to determine exactly the particle size that severed the SEDS–2 tether with the information available. If this 0.014-cm-diameter meteoroid particle (low material density) with an average impact velocity of 20 km/sec was used to find the diameter of an aluminum test particle with a velocity of 7 km/sec and equally penetration capability, the test particle diameter is in the same order of magnitude as those determined by tests discussed in section 5.3 for the SEDS–3 tether.

### 5.3 Third SEDS (SEDS/SEDSAT) Mission

The M/OD impact damage analysis for the third SEDS mission is again similar to the ones for the first and second SEDS missions. The material and tether diameter remained unchanged for the third SEDS mission, so the determination by analysis of the critical particle size also remained the same. However, the mission parameters had changed and the technique used for the HVI tests had improved, so the resulting probability of no tether severing is different. In addition, the M/OD impact damage analyses for SEDS–3 hardware and the SEDSAT satellite were performed.

Major differences among the SEDS–1, –2, and –3 missions were that the first two SEDS missions used the second stage of a Delta II expendable rocket as a launch platform and the third mission will use the shuttle orbiter as a launch platform. The use of shuttle orbiter and the involvement of crew members increased the awareness of possible endangerment of the crew members due to the entanglement of a severed tether with the shuttle orbiter. This concern was further emphasized as a result of the on-orbit severing of the SEDS–2 tether as discussed in the previous section.

A range of the possible critical aluminum test particle sizes were estimated using several single-plate penetration equations, including those of Fish-Summers and Schmidt-Holsapple. These critical aluminum test particle sizes were predicted to be between 0.010 and 0.040 cm.[7] Until the HVI tests had determined the critical aluminum test particle sizes, three possible critical aluminum test particle sizes (0.015, 0.025, and 0.035 cm in diameter) were used to perform the M/OD impact damage analysis for the SEDS/SEDSAT mission.

The probabilities of no tether severing by the M/OD particle impacts were calculated as shown in figure 12, using three possible critical test particle diameters as a function of the mission time. The M/OD impact damage analyses for the SEDS–1 and –2 missions used the average tether altitude. However, for the SEDS/SEDSAT mission, altitudes were calculated as a function of the time based on the tether deployment and satellite launch sequences for a better analysis. The M/OD models used for the SEDS/SEDSAT mission were those defined in NASA TM–4527.[2] These models are the same as the ones from NASA SSP–30425, Rev. A, Change A1. However, the models defined in NASA SSP–30425 are documented specifically for the *International Space Station* Program, and the models defined in NASA TM–4527 are intended for use by any spacecraft program and are also the most current published models.

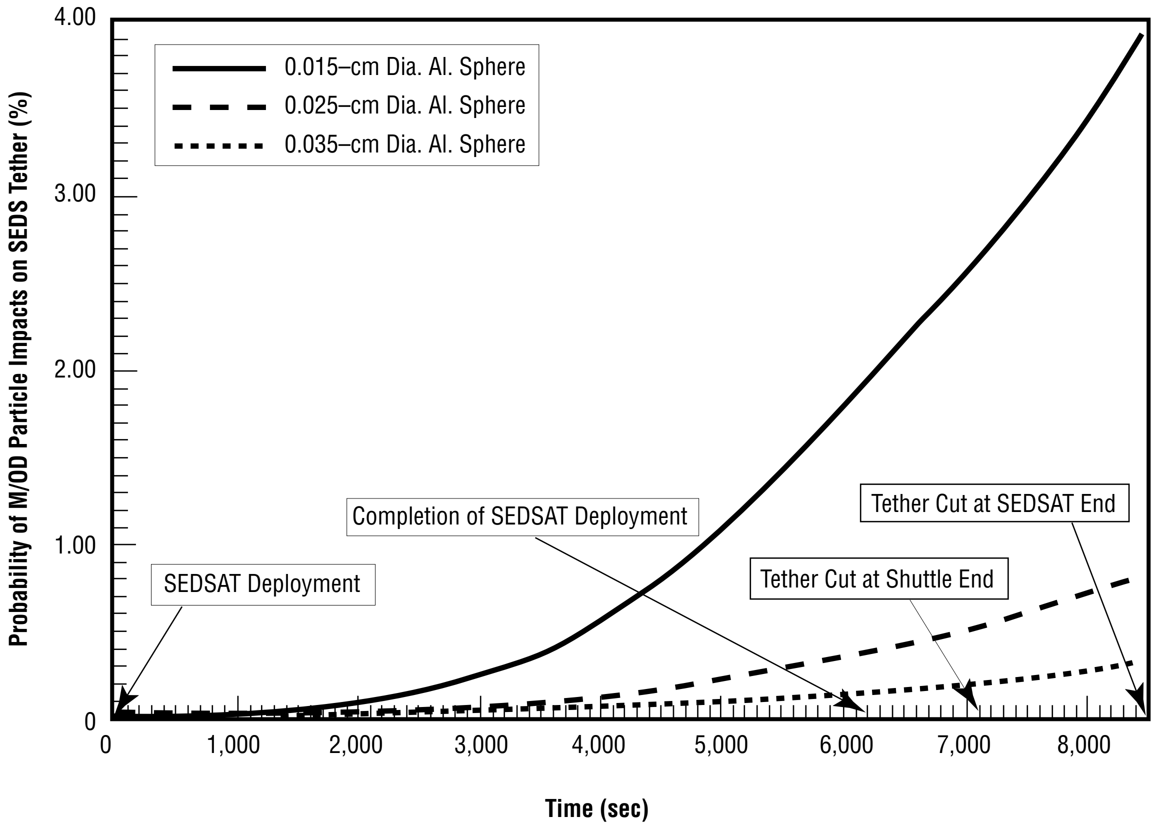


Figure 12. Probability of M/OD particle impacts on tether as a function of time for tether survivability analysis for 57° inclination using three possible critical aluminum test particle sizes.

Previous CTH hydrocode simulations predicted the critical orbital debris particle sizes required to sever the tether. However, this time the CTH hydrocode was used to help predict the critical aluminum test particle sizes, and procedures used and simulation results are discussed in detail in section 4.

After the SEDS–2 tether was severed by a possible meteoroid, as discussed in the previous section, a series of HVI tests were started at JSC's HIT–F to better define the critical test particle sizes. This task was continued into the SEDS/SEDSAT mission, and the technique was improved over time. In addition, another series of HVI tests were performed at AEDC to develop another technique and obtain more definitive test results. The technique used by AEDC was expected to increase the chances of impacting multiple targets by shooting multiple particles instead of shooting a single particle at multiple tethers used at JSC. The hydrocode simulation results indicated that the critical aluminum test particle sizes would be between 0.015 and 0.020 cm in diameter, and these sizes were much smaller than the particle sizes used for the HVI tests. Thus, smaller glass test particle sizes were requested for the remaining tests to verify the computer simulation results and to better determine the critical aluminum test particle sizes. The test results indicated that the glass test particles impacting tether samples at approximately 7 km/sec seemed to be severing the tether when the glass test particle sizes were between 0.030 and 0.035 cm. These sizes are smaller than ones predicted by previous test results, but they are still larger than ones predicted by computer simulations.

The probabilities of no failure of the SEDS/SEDSAT hardware; i.e., the Deployer Canister, the Electronics Box, the Brake/Cutter Assembly, and the Tether, by the M/OD particle impacts were initially estimated for the M/OD environments using three possible critical aluminum test particle sizes. Table 6 shows the analysis results with the mission duration of 2.33 hr for tether and hardware and 3 yr for SEDSAT satellite, where PNS and PNCF are defined as the probability of no severing (the tether) and probability of no critical failure, respectively. The critical failure of the hardware is defined as any M/OD particle impact that will cause functional failure.

Table 6. Probability of no failure of the SEDS–3 hardware and tether (unloaded) by the M/OD particle impact damages.

| Aluminum Test Particle Size to Sever the Tether (cm) | Tether PNS (%) | SEDS–3 Hardware PNCF (%) | SEDSAT PNCF (%) | Total PNCF (%) |
|---|---|---|---|---|
| 0.0150 | 96.15 | 99.99 | 99.69 | 95.84 |
| 0.0250 | 99.20 | 99.99 | 99.69 | 98.89 |
| 0.0350 | 99.70 | 99.99 | 99.69 | 99.39 |

Based on the HVI test results discussed previously (for the unloaded case), the probability of no tether severing for the SEDS/SEDSAT mission was estimated to be better than 99.2 percent for both the M/OD environments, and the probability of no failure of the SEDS–3 hardware was estimated to be 99.99 percent. The probability of no failure of the SEDSAT satellite for its 3-yr mission life was estimated to be 99.69 percent. For the tether, the predicted critical particle sizes and exposed areas to the M/OD environments after deployment are given in table 7.

Table 7. M/OD particle impact damage analysis results for SEDS–3 tether (unloaded).

| | |
|---|---|
| Exposed Area to Orbital Debris Environment | 82.65 $m^2$ |
| Exposed Area to Meteoroid Environment | 47.12 $m^2$ |
| Aluminum Test Particle Size to Sever the Tether | 0.0300 cm |
| Orbital Debris Particle Size to Sever the Tether | 0.0187 cm |
| Meteoroid Particle Size to Sever the Tether | 0.0208 cm |
| Probability of No Tether Failure | >99.20% |

Based on the analysis performed on the loaded tether case for the SEDS–1 and –2 missions, the same analysis for the SEDS/SEDSAT mission was performed for the sake of comparison, using the same M/OD particle sizes. The probability of no tether failure predicted for the SEDS/SEDSAT mission ranged between 79 and 93 percent, which is better than those predicted for the SEDS–2 mission, attributable to the shorter SEDS/SEDSAT mission duration. The analysis result is tabulated and shown in table 8.

Table 8. M/OD particle impact damage analysis results for SEDS–3 tether (loaded).

| | |
|---|---|
| Exposed Area to Orbital Debris Environment | 82.65 $m^2$ |
| Exposed Area to Meteoroid Environment | 47.12 $m^2$ |
| Orbital Debris Particle Size to Sever the Tether | 0.0036–0.0062 cm |
| Meteoroid Particle Size to Sever the Tether | 0.0031–0.0054 cm |
| Probability of No Tether Failure | 79%–93% |

An additional M/OD damage assessment was performed to support the safety hazard analysis. The critical time, beginning when the tether is deployed at 19 km long and ending when the tether is cut at the shuttle end, was considered for this study. The three possible critical aluminum test particle sizes from table 6 were used to calculate the probabilities of no tether severing as a function of the time (unloaded case). As a result, a new set of probabilities of no tether severing was estimated as 99.86 percent for 0.025 cm in diameter and 99.95 percent for 0.035 cm in diameter as the critical aluminum test particle sizes. Figure 13 shows these analyses results.

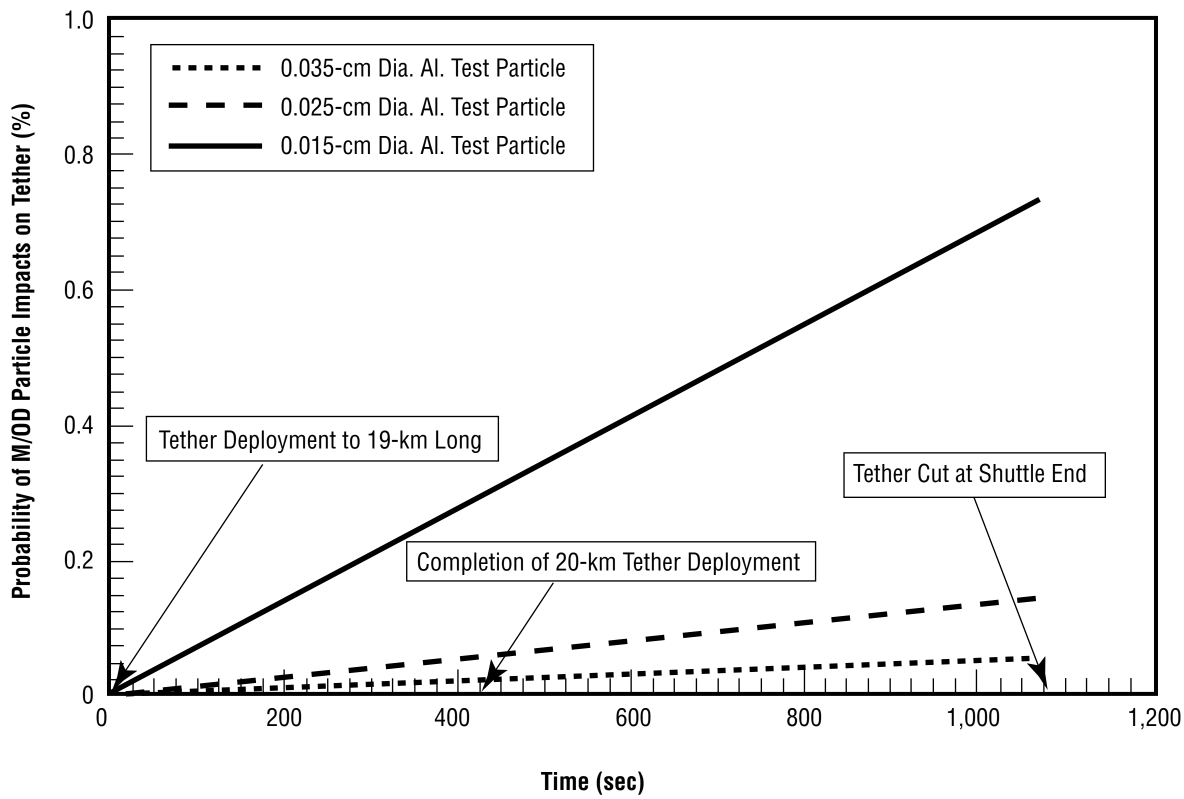


Figure 13. Probability of M/OD particle impacts on tether as a function of time for safety hazard analysis using three possible critical aluminum test particle sizes.

## 6. COMPLYING WITH NASA MANAGEMENT INSTRUCTION TO LIMIT THE ORBITAL DEBRIS GENERATION

The NASA Management Instruction (NMI) 1700.8 entitled “Policy to Limit Orbital Debris Generation” was issued in April 1993, requiring each program office to conduct a formal assessment of the potential to generate orbital debris. Then, the NASA Safety Standard (NSS) 1740.14 entitled “Guidelines and Assessment Procedures for Limiting Orbital Debris” was issued in August 1995 as a companion to NMI 1700.8 in order to provide each NASA program office with specific guidelines and assessment methods to assure compliance with the NMI.

The M/OD damage analyses performed on the SEDS hardware and tether for the three SEDS missions by the authors were to determine the survivability of the SEDS hardware and tether to the meteoroid and existing orbital debris environments. Therefore, no analysis was performed by the authors to determine the potential to generate orbital debris from the SEDS hardware and tether. However, this analysis was performed for the SEDS/SEDSAT mission by the Electromagnetics and Aerospace Environments Branch of MSFC after NSS 1740.14 was issued.

Any future space tether missions are now required to comply with this NMI by performing the analysis to determine the potential to generate orbital debris, and it is still recommended to determine the survivability of the space tether to the meteoroid and ever-worsening orbital debris environments.

## 7. RECOMMENDATIONS/CONCLUSION

The threats from the M/OD particle impacts on SEDS hardware or tether are very important issues for the success of any SEDS missions. Grazing or partially penetrating impacts can cause degradation of the tether's load-carrying capability over time and will lead to eventual sever of the tether. A more serious concern for the short-duration missions is the possibility of severing the tether instantly. Because of the extremely long length of a tether, it has relatively large exposed areas to the M/OD environments, although the tether diameter is very small. This concern was especially emphasized after the SEDS–2 tether was severed by a possible meteoroid particle impact. The difficulty in determining the critical M/OD particle sizes required to sever the tether was compounded by the unknowns in the capability of the tether material; i.e., Spectra 1000, to resist the M/OD particle impacts, and by the incomplete development of new or unique HVI test techniques for tethers. The importance of developing new or unique HVI test techniques for tethers is shown by these test results.

A series of the computer hydrocode simulations and HVI tests were performed to help determine the M/OD particle sizes expected to sever the tether. A series of analyses were performed using the metallic-based, empirically developed, single-plate penetration equations to estimate the probabilities of no tether severing and no SEDS hardware failures. The HVI test results indicated that the critical aluminum test particle sizes required to sever the tether would be between 0.030 and 0.035 cm for the unloaded tether.

The results of the work presented in this paper indicate that any short-duration space tether mission will have a high probability of mission success in the M/OD environments. However, if the mission duration extends into days or months, if a smaller or longer tether is used instead of the current one, or if less durable tether materials or designs are used, then the chance of severing the tether caused by the M/OD particle impacts increases significantly. Also, if the tether stays in orbit for more than a few hours after the completion of the mission, the chance of severing the tether significantly increases. In addition, these orbiting severed tethers may become hazardous to other spacecraft before they reenter the Earth's atmosphere and may violate NMI 1700.8 "NASA Policy to Limit Orbital Debris Generation." It is recommended that future missions consider the threats from the M/OD environments from the beginning of the program, from tether material and design selection to placement/location of the tether/satellite system on the launch vehicle or shuttle. The success of any tether mission will depend on the consideration given to the effects of the M/OD environments throughout program and mission planning.

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**13. ABSTRACT** *(Maximum 200 words)*

The Small Expendable Deployer System (SEDS) was designed to deploy an endmass at the end of a 20-km-long tether which acts as an upper stage rocket, and the threats from the meteoroid and orbital debris (M/OD) particle environments on SEDS components are important issues for the safety and success of any SEDS mission. However, the possibility of severing the tether due to M/OD particle impacts is an even more serious concern, since the SEDS tether has a relatively large exposed area to the M/OD environments although its diameter is quite small. The threats from the M/OD environments became a very important issue for the third SEDS mission, since the project office proposed using the shuttle orbiter as a launch platform instead of the second stage of a Delta II expendable rocket, which was used for the first two SEDS missions.

A series of hypervelocity impact tests were performed at the Johnson Space Center and Arnold Engineering Development Center to help determine the critical particle sizes required to sever the tether. The computer hydrodynamic code or hydrocode called CTH, developed by the Sandia National Laboratories, was also used to simulate the damage on the SEDS tether caused by both the orbital debris and test particle impacts. The CTH hydrocode simulation results provided the much needed information to help determine the critical particle sizes required to sever the tether. The M/OD particle sizes required to sever the tether were estimated to be less than 0.1 cm in diameter from these studies, and these size particles are more abundant in low-Earth orbit than larger size particles. Finally, the authors performed the M/OD damage analyses for the three SEDS missions; i.e., SEDS–1, –2, and –3 missions, by using the information obtained from the hypervelocity impact test and hydrocode simulations results.

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